MANAGING DELTA ALGAL-RELATED DRINKING WATER QUALITY: TASTES AND ODORS AND THM PRECURSORS

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INTRODUCTION

Municipal water utilities are facing ever increasing demands to improve water quality. This situation is causing many water utilities to initiate new treatment processes or approaches as well as to improve the performance of existing treatment works. These various improvements are adding to the cost of producing a potable and palatable domestic water supply. Many water utilities are finding that increased urbanization and industrialization of their water supply watersheds is causing increased contaminant loads that must be removed in the treatment works. Both of the above mentioned factors are causing water utilities and water quality regulatory agencies to consider the feasibility of controlling domestic water supply quality by controlling contaminant concentrations at the water supply source. This paper presents an overview of the current information on some programs that have been, or could potentially be, successful in improving domestic water supply raw water quality for those water utilities that use the Sacramento-San Joaquin River Delta as a water supply water source.

DELTA THM PRECURSOR SOURCES AND THEIR CONTROL

One of the most significant water quality problems for domestic water supply utilities that utilize the Delta as a source is the formation of THMs in the waters disinfected by chlorine or other strong oxidants, such as ozone in the presence of bromide. THMs arise from chlorine (primarily free chlorine) reacting with dissolved and particulate organic matter present in the raw water to form a group of low molecular weight halogenated hydrocarbons, such as chloroform. In the presence of bromide in the raw water, strong oxidants, such as free chlorine and ozone, oxidize the bromide to bromine. The bromine in turn reacts in a similar manner to free chlorine, forming brominated THMs.

The presence of bromide in a water supply is of particular significance as a THM precursor because it is much heavier than chlorine and therefore, since the THM MCL (maximum contaminant level) is based on a mass per volume concentration, a brominated THM is a more important species than its equivalent chlorinated form with respect to meeting the MCL. It also appears that bromine may be a more effective halogenating agent than chlorine with the result that higher THM levels on a molar basis are formed when bromide is present compared to when it is absent. Bromides are frequently associated with seawater and brines. It is therefore obvious that water utilities with any sources of controllable bromide within their raw water supply should aggressively require control of those sources to the maximum extent possible.

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Until recently, few water utilities determined the bromide concentration of the raw water supply with the result that there is very limited information available today on the pollution of water supplies by bromide. For seawater systems, the chloride to bromide ratio in accord with the law of constant relative proportions is a fairly well-defined ratio of about 0.003. As a result, for freshwaters contaminated with seawater, such as occurs in part of the Sacramento-San Joaquin River Delta (Delta), it is possible to estimate the bromide concentration of the water based on the chloride concentration. For other sources of bromide, however, such as an oil field brine or other brines, the seawater ratio may

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Published in "Protecting Drinking Water Quality at the Source," Proceedings of a Conference, University of California Water Resources Center Report no. 76, October (1991).

not be applicable to waters contaminated by brines from other sources. Caution should therefore be exercised in a complex system such as the Sacramento-San Joaquin River Delta system in assuming that all tributaries of the Delta have chloride to bromide ratios the same as seawater. While this could be the case, since the export of Delta water contaminated with seawater results in some of this water being returned to the Delta through the San Joaquin River system, it is important to verify, for this and other similar situations, that chloride concentrations can be used to estimate the bromide content of the water.

There is considerable justification for limiting the amount of seawater that enters the Delta in order to reduce the bromide input to this system and to reduce the potential for brominated THM formation. In the fall of 1990, the State Water Resources Control Board Delta Municipal and Industrial Water Quality Work Group made a recommendation to the California Water Resources Control Board to manage water quality within the Delta system so that the freshwater outflows from the Delta to the San Francisco Bay system will be sufficient to limit the saltwater migration into the Delta for the purpose of controlling the introduction of bromide in the seawater into Delta waters that are exported or used directly for municipal water supply sources. This is a highly justified, source-water-quality control effort that is under review by the State Water Resources Control Board at this time.

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Another example of a situation where bromide control in a source water was highly justified occurred in the work that the authors did with the Canadian River Municipal Water Authority, which utilized Lake Meredith in West Texas as a domestic water supply source (Lee and Jones, 1983). This lake received brine drainage to tributaries. This brine was derived from natural sources in the Canadian River watershed. It contained elevated concentrations of bromide which led to elevated brominated THMs in water supplies that use Lake Meredith water as a source. Efforts were made by the Canadian River Municipal Water Authority to control the amount of brine input to the tributaries of the reservoir for the purpose of limiting brine, and specifically bromide, input to the waterbody.

While it has been known for many years that controlling the concentration of organic precursors of THMs by their removal in treatment works can control THM concentrations, surprisingly little attention has been given to attempting to understand, and where possible to control, organic THM precursors at the source. This is an area that deserves attention and that could be a potentially significant approach that could be utilized by some water utilities for controlling excessive THMs. The work of Randtke and his associates (Randtke et al. 1988) has provided some insight into the potential sources of THM precursors. Table 1 presents a summary of the Randtke et al. data on the concentrations of THM precursors as measured in a standardized chlorination test (THMFP--trihalomethane formation potential) in various runoff waters and samples of effluents, etc. It is readily apparent from this and other work that certain types of land use and wastewater discharges are particularly significant sources of THM precursors. Randtke et al. (1988) found that while THM precursor concentration in waters from various sources varied greatly, the THM yield as measured as THMFP concentration per mg carbon was remarkably constant. This points to the potential that for many situations controlling the total organic carbon (TOC) content of the water is a potentially reliable basis for controlling THM precursors. Obviously, there is need for additional study of the applicability of the Randtke et al. results to other areas to be certain that the relatively constant ratio that they found between THM formation potential and TOC is found in other areas. There is some indication in the literature that this may not be the case. Water utilities and water pollution control agencies would therefore need to make an evaluation of this relationship of potentially significant sources of organic THM precursors in their watersheds in order to determine if the THM precursor source control program could be focused on controlling TOC discharge to waters that are tributary to the water supply source for the water utility.

While THM organic precursors are derived from natural sources, such as decaying vegetation, etc., the activities of man through municipal and industrial wastewater discharges and agricultural runoff and

D-044488

drainage can significantly increase the THM precursor concentrations in a water supply. If a much better understanding existed of THM precursor sources and the amounts of precursors derived from various types of land use, then it might be possible to develop approaches that could effectively reduce precursor input. An example of this type of work is currently underway in the Delta by the California Department of Water Resources (DWR) and a paper on the results of this work was presented by Woodard (1991) at this conference. The DWR study focuses on Delta sources of THM precursors. It, however, does not go far enough back into the tributary sources of the Delta to understand the specific sources of THM precursors that exist in the major tributaries to the Delta upstream of the Delta. It is clear from the Department of Water Resources monitoring data (DWR 1989) that a significant amount of THM organic precursors are brought into the Delta from tributary sources to the Delta. DWR found that the five-year (1983-1987) median (THMFPs) at Greene's Landing on the Sacramento River was 260 μg/L. At Vernalis on the San Joaquin River it was 450 μg/L, while the five-year median at the bank's export point was 490 μg/L. While it would be necessary to actually compute input loads of THM organic precursors from the Sacramento and San Joaquin rivers based on concentrations and flow data, it is clear that a significant amount of THMFPs are added to the Delta each year from Delta tributary sources and that a significant effort should be made to understand the specific contributions of these various sources since it could lead to the development of control programs that could influence THM formation in water supplies that use the Delta as a water supply source. It is therefore evident that the DWR current studies in this area should be expanded to include not only the definition of in-Delta sources but also upstream of the Delta sources of THM organic precursors.

It has been known for some time from work in various parts of the United States that waters in contact with high organic soils, such as peat, which occur in some parts of the Delta, can have greatly elevated concentrations of organic THM precursors. From a review of the Department of Water Resources' monitoring data on waters added to and taken from agricultural lands within the Delta, it has been found by the authors that the waters diverted from the Delta channels to agricultural lands and then pumped back to the channels will typically show a 1,000 to 1,500 μg/L increase in THM formation potential when corrected for evaporative concentration. It is evident from examination of the total dissolved solids (TDS) in the waters diverted from the channels to agricultural lands and the waters pumped back to the channels from these lands, that there is about a two- to three-fold evaporative concentration of salts on some of the agricultural lands within the Delta. This could mean that on the order of one-half of the increase in THM precursors discharged from Delta agricultural lands to the channels could be derived from evaporative concentration on the agricultural lands. The other half would be derived from leaching from peat soils and any crop or other plant residues present in or on the soil. It is likely that there is some change in the type of compounds that make up the organic precursors derived from the agricultural lands due to sorption, microbial transformation, and desorption-solubilization processes; and therefore, the chemical makeup of the dissolved organic carbon (DOC) added to agricultural lands will likely be different from that discharged from them. This could affect the relationship between DOC and THM formation potential since only a small part of the DOC is converted to THMs during disinfection processes involving chlorine or other strong oxidants in the presence of bromide.

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It is recommended that an aggressive program be developed to reduce the amount of organic THM precursors added to Delta waters from agricultural as well as other sources. The first step in developing such a program is to better understand the relative significance of each potentially significant source for the Delta in each of its major tributaries. This program should include determination of specific sources of THM precursors that contribute more than about 10 percent of the total to a Delta tributary as well as within the Delta. These sources should in turn be investigated to understand the specific sources of THM precursors within the source and the potential control programs that could be developed to reduce the amount of THM precursors present in the raw water supplies for the utilities that utilize water from the Delta. Similar

Table 1

THM FORMATION POTENTIAL IN RUNOFF AND POINT-SOURCE SAMPLES

Site Description	DOC mg/L	TOC mg/L	THMFP µg/L
Urban-Commercial	17.8	67.0	1,152
Industrial Landfill	257.0	337.0	1,555
Construction Landfill	6.06	19.9	967
Terraced/Tiled Farmland	4.52	203.4	4,329
Non-terraced Farmland	4.92	7.55	400
Burned Bromegrass Land	6.39	7.93	409
No-till Farmland	4.72	7.09	482
Cattle Feedlot	64.1	382.7	13,482
Tilled Farmland	16.7	29.6	1,651
Swine Feedlot	13.0	26.5	1,383
Cattle Feedlot	71.1	122.5	4,747
Soybean Field	9.92	13.6	710
Corn Field	3.74	17.2	591
Corn Field	13.4	17.3	1,008
Urban Construction	3.03	22.7	1,486
Urban Residential	5.12	6.99	395
Industrial Park	4.48	6.72	274
Shopping Center	3.09	5.22	268
Municipal Secondary Effluent (Activated Sludge)	9.15	9.57	304
Municipal Secondary Effluent (Stabilization Pond)	16.4	41.4	1,093
Municipal Secondary Effluent (Stabilization Pond)	32.7	55.3	926
Municipal Secondary Effluent (Stabilization Pond)	28.4	54.2	1,027
Sanitary Landfill Runoff Pond	3.0	3.6	154
Refinery Effluent	26.9	42.0	2,071
Cellophane Manufacturing Effluent	5.4	8.3	272
Power Plant Cooling Water	7.0	8.4	315
Power Plant Cooling Water	7.0	7.8	340
Power Plant Ash Pond Effluent	3.7	3.9	151
Power Plant Ash Pond Effluent	4.7	6.1	421
Electroplating Plant Effluent	9.4	10.7	156
Meat Packing House Effluent	16.1	20.8	819
Fertilizer Plant Wastewater Pond	11.2	16.2	242

THM YIELDS OF RUNOFF SAMPLES

Sample Group	No.of Samples	Average THMFP (umoles/mgC)
All Samples	18	0.37 ± 0.14
Urban Runoff	6	0.39 ± 0.14
Agricultural Runoff	11	0.39 ± 0.11
Feedlot Runoff	3	0.35 ± 0.07
Farmland Runoff	8	0.41 ± 0.12

After Randtke et al. (1987)

kinds of programs should be conducted by water utilities throughout the country that face problems with excessive THM formation.

Ultimately, it should be possible to develop THM precursor export coefficients similar to the export coefficients that have been developed by Rast and Lee (1983) for nitrogen and phosphorus where certain types of land use or drainage would be expected to contribute certain amounts of THM precursors on a unit area per unit time basis. This would require determining the concentrations of THM precursors from various types of sources at fairly frequent intervals of one to no more than two weeks over at least a one and preferably two-year time period while the flow of the source is also being measured. The objective of such measurements would be to develop mass THMFP per hectare per year data for runoff samples. For effluent samples, the total mass loading of THMFPs per year would be determined. This could in turn be potentially related to a population equivalent for municipal wastewaters which reflects the type and degree of treatment provided by the treatment works. For industrial wastewaters, it should be possible to develop a THMFP equivalent per unit of manufactured product or some other similar basis which relates the wastewater loads to industrial activity. It should be readily possible to determine a relationship between TOC removal in a wastewater treatment plant for certain types of wastes and a THMFP removal ratio.

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The development of THM precursor export coefficients could be highly instrumental in having regulatory agencies begin to control municipal, industrial, and agricultural activities that represent significant sources of THM organic precursors for domestic water supplies. THM precursors in wastewaters, urban and agricultural drainage, etc. will ultimately be considered pollutants that have to be controlled through discharge permits in much the same way as other contaminants are being controlled today. This situation will likely arise out of the fact that while in the past it has been possible to modify disinfection practices to meet THM MCLs, in the future, this approach will not likely be possible. As a result, it will become necessary to focus THM control on significantly reducing THM precursor sources for domestic water supplies. For further information on this topic, consult the paper by Glaze (1991) presented at this conference.

ROLE OF ALGAE AS THM PRECURSOR SOURCES

It has been known for many years that the chlorination of laboratory algal extracts can lead to high concentrations of THMs. This has caused a number of investigators, principally Hoehn and his associates (Hoehn et al. 1980) to investigate whether algae could be a significant source of THM precursors for domestic water supplies. Hoehn has found high concentrations of THM precursors in the presence of algal blooms in a reservoir in Virginia. Randtke et al. (1988) conducted a series of studies specifically designed to examine the role that algae play in serving as THM precursors for the waterbodies that they investigated. They concluded that algae and other aquatic plants are not important sources of THM precursors in these waters. It appeared from their work, that while the algae and higher aquatic plants could serve as a THM precursor source, any precursors developed by or from them rapidly disappeared from the water.

It has been reported by Lee (1973) that eutrophication of Lake Mendota located in Madison, Wisconsin that has occurred over the last fifty years or so has not changed the dissolved organic carbon (DOC) of the lake water. For this waterbody at least, the DOC is primarily derived from terrestrial, land-based sources rather than aquatic plant sources (including algal).

Walker (1983) has reported correlations between the phosphorus content of domestic water supply lakes and reservoirs and the THMs formed in these waters upon disinfection with chlorine. The implication is that since the phosphorus content of the lake correlates with algal chlorophyll, the algae are an important source of THM precursors. However, in the opinion of the authors, the correlation of phosphorus with THMs is spurious. It is likely that in many watersheds, phosphorus export from the land is correlated with DOC export from the land. Therefore, Walker's correlation approach cannot be judged as a valid assessment approach for determining the role that algae play as THM precursor sources.

From the information in the literature and the authors' experience, it appears now that it is important to distinguish between terrestrial and aquatic plants as THM precursor sources. While both terrestrial and aquatic plants can serve as important sources of THM precursors, it appears that the aquatic plant (algae and many macrophytes) produce THM precursors which are transitory-labile in aquatic systems. Terrestrial vegetation, on the other hand, tends to produce THM precursors, some of which are highly refractory-persistent in soils and aquatic systems. It has been suggested by Folan (pers. comm. 1989) that this difference may be related to the lignin content of terrestrial plants. Lignin appears to be converted to highly persistent DOC. Since aquatic plants normally have little or no lignin content, their decay, while initially producing large amounts of THM precursors, upon further microbial transformations, produce decay products which do not lead to THM formation.

While the literature on the persistence of algal-derived THM precursors is very limited, it appears to the authors that at least under warm water conditions of 15°C or greater the algal-derived THM precursors decay sufficiently in a period of a few days to a week to non-precursor compounds. This decay would be expected to be somewhat slower in cold waters. There is obvious need to conduct indepth studies on the formation and decay of algal-derived THM precursors in various types of aquatic systems of potential importance to water utilities. Such studies will provide utilities with the information they need to determine for their particular system whether THM precursors are derived at any time during the year to a significant extent from algal blooms in their raw water supply.

For the case of a water utility with highly eutrophic raw water supplies, algae will represent a significant source of additional THM precursors, and there will be additional justification for controlling algal populations through the use of nutrient (phosphorus and/or nitrogen) input control. Further, it may be appropriate for some utilities to develop pretreatment of their raw water by biological means in order to bring about the decay of the algal-derived THM precursors before disinfection. This could be practiced by holding the water in the dark for a sufficient period of time to allow microbial transformation of the algal-derived THM precursors. It is likely that gentle stirring of the water such as with large paddles used in flocculation basins could accelerate the growth of bacteria which would bring about these transformations. It may be desirable to develop a modified version of a rotating biological contactor used for wastewater treatment as a means of developing sufficient bacterial populations for pretreatment of the raw water. Such an approach would have a high probability of rapidly removing algal-derived precursors without stimulating additional algal growth or other raw water quality problems.

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Water utilities that have high THM precursor concentrations in their raw water and have algal populations of greater than 10 to 20 $\mu g/L$ planktonic algal chlorophyll in this raw water near the point of intake should determine if a significant part of the THM precursors are lost upon aeration and/or stirring of the water in the dark over a period of several days. If this does occur, then it may be possible to devise systems to accelerate the decomposition of labile precursors and thereby reduce the precursor load on the treatment works.

The Delta waters typically would be classified as moderately to highly eutrophic and would be expected to have a variety of algal-related domestic water supply quality problems, such as tastes and odors. It appears that the Contra Costa Water District and those whom this district supplies could expect that at least part of their THM precursor concentrations at some times in the year are derived from algae and therefore are potentially labile. This is an area that should be investigated since ultimately when the control of THM precursors from peat soils and other activities within the Delta is practiced, it could be that algae may become a very important part of the precursor sources for some of the water utilities drawing water from the Delta.

EUTROPHICATION OF DOMESTIC WATER SUPPLY LAKES AND RESERVOIRS

The eutrophication (excessive fertilization) of domestic water supply lakes and reservoirs is a well known cause of water supply quality deterioration. The growth of planktonic algae in domestic water supplies is known to cause increased tastes and odors, shortened filter runs, increased chlorine demand, increased turbidty, and, for some situations, increased trihalomethane (THM) precursors. Gilbert (1991) reported at this conference that surveys taken of consumer satisfaction with the aesthetic quality of a domestic water supply found that for the East Bay Municipal Water District about 70 percent of the respondents indicated that they found that their water supply aesthetic quality was satisfactory. For the San Francisco Bay region as a whole, consumer satisfaction was about 35 percent. For the state as a whole it was about 25 percent. Since taste and odor problems are one of the primary causes of consumer dissatisfaction with water supply quality and since in California water supply taste and odor problems tend to be of algal origin, algal growth in surface water supplies is a frequent cause of significant algal- related taste and odor problems. For additional information on the impact of algae on domestic water supply taste and odors and other water quality problems, consult Palmer (1959).

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Many water utilities cannot or do not practice algal control through controlling algal blooms with copper sulfate, because of the concern about the toxicity of copper to aquatic life in lakes and reservoirs used for recreational purposes and/or the cost of treating some lakes and reservoirs with copper sulfate. While typical eutrophication control programs based on reduction of algal nutrient input to a lake or reservoir that have been adopted across the U.S. focused primarily on managing the impacts of algae on recreational use of the waters where the algal-related problems were floating scum, decaying algae on the beach, malodorous conditions, low light penetration, dissolved oxygen depletion in hypolimnetic (bottom) waters, fish kills, etc., one of the benefits of such programs has been improvement in the domestic water supply raw water quality. With increasing constraints on water utilities' use of copper sulfate, water utilities should give greater consideration to controlling algal growth in their lake or reservoir water supply by limiting algal nutrients added to the waterbody from its watershed.

Lee and Jones (1988a) presented a review of the North American experience in eutrophication control through phosphorus management. As they discussed, it has generally been found throughout the world that, with few exceptions, controlling the phosphorus input to a freshwater lake or reservoir can, if practiced to a sufficient extent, reduce the amount of algae that would develop in the waterbody. Since typically algal-related domestic water supply quality problems are related to the numbers of algae present, reducing algal biomass in a water supply reservoir is in the direction of reducing domestic water supply raw water quality problems due to algae. There are, however, *significant* differences in the ability of various types of algae to cause domestic water supply quality problems. Certain types of algae are well known for their highly obnoxious, very potent odors associated with their presence in a water; this is especially true for certain blue-green algae which are known to have odors that are characterized as "pig-pen-like." Normally, however, it is found that reducing the overall nutrient (phosphorus) loads to a lake or reservoir tends to be in the direction of not only reducing total algal biomass, but also reducing the frequency and severity of highly obnoxious algal blooms (Lee 1973).

MANAGEMENT OF EXCESSIVE FERTILIZATION IN THE DELTA AND IN WATER SUPPLY RESERVOIRS

A review of the State of California Department of Water Resources Delta monitoring data for the period 1983 through 1989 shows that the amount of planktonic algal chlorophyll present during the period May through July at the Clifton Court Forebay averages about 7 to 25 μg/L. Many of the values are in the 10 to 20 μg/L range with some values exceeding 50 μg/L. As discussed below, algal growth within the Delta is about what would be expected based on the aquatic plant nutrients (phosphorus) available for their growth within the system. Based on the experience of the authors in relating planktonic algal chlorophyll to domestic water supply quality problems, it is typically found that when the planktonic algal chlorophyll exceeds around 7 to 10 µg/L that water utilities can experience significant algal-related water quality problems.

It is well known (see Palmer 1959) that algal-related domestic water supply problems depend on the specific types of algae present. Some algae at planktonic algal chlorophyll concentrations in the 20 µg/L range cause few problems other than shortening filter runs. On the other hand, some algal blooms on the order of 5 to 10 µg/L chlorophyll cause severe taste and odor problems. There are situations, such as are occurring in Lake Tahoe (Lee and Jones 1991), where taste and odor problems are found in water supplies in which the planktonic algal chlorophyll is on the order of 1µg/L. Situations of this type appear to be very rare, however. There is general agreement that any time the planktonic algal chlorophyll concentration is above 25 µg/L, water utilities can expect to experience significant algal-related water quality problems.

Based on the authors' discussions on algal growth within the Delta system with various individuals, it has been found that there is considerable confusion about how well the Delta grows algae compared to what it should be doing based on its nutrient loads and characteristics. It has been found by the authors that the amount of planktonic algal chlorophyll--as measured by the DWR Water Quality Surveillance Program from 1983 to 1989, at the Clifton Court sampling station for the period May through July--is in reasonably good agreement with the amount of planktonic algal chlorophyll that would be expected at this location based on the phosphorus content of the water at that location. The predicted planktonic algal chlorophyll is on the order of 10 to 15 µg/L. The measured average values vary from 7 to 25 µg/L. The predicted values are based on predictions by the use of the Vollenweider-OECD modeling relationship discussed by Jones and Lee (1986). As discussed below, the Delta appears to have about a 30-day hydraulic residence time during the summer months, and therefore, there is ample time for algae to develop to the extent allowable based on the nutrients available.

Review of the DWR data shows that nitrogen is not the limiting element controlling algal growth in the Delta. There are significantly surplus amounts of nitrogen compared to what is needed to support the amount of algal growth that is occurring. Further, as shown in the work by the authors (Jones and Lee 1986) light is not a significant limiting factor in controlling algal growth within the Delta over the control that light limitation has in controlling algal growth in other waterbodies, i.e., the color of Delta waters is not sufficient to significantly affect the biomass of algae that develops in these waters based on their nutrient content.

It is clear from these results that the Delta is growing algae in about the same way as waterbodies located throughout the world grow algae relative to their phosphorus loads. This is not unexpected since the stoichiometry (chemical composition) of algae is the same worldwide. The fact that some parts of California have a more arid climate does not, as is sometimes asserted, cause algae in this area to be different from algae in other areas of the world. It is also clear that water utilities that use Delta water as a raw water source can expect to have algal-related water quality problems in their raw water supplies. It would be expected that water utilities using Delta waters would experience significant taste and odor problems and that there would be a potential for algal-derived THM organic precursors in the water.

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In addition to being concerned about algal-derived tastes and odors and THM precursors for those utilities who take water directly from the Delta and treat it shortly after extraction, concern should also be focused on the development of algae in reservoirs that are used to store exported Delta water before its use as a domestic water supply source. Under these conditions, it is possible that severe algal-related raw water quality problems could occur as a result of algae developing in the reservoir before the water is used for domestic purposes. Some water utilities, such as the Santa Clara Water District, have reported severe algal-related water quality problems in waters derived from reservoirs that were filled with Delta water. This district has found a correlation between planktonic algal chlorophyll and taste and odor problems in their raw water source. According to Means (1991), several of the

Metropolitan Water District reservoirs, such as Perris Reservoir, have experienced significant algal-related taste and odor problems. Other reservoirs in the Metropolitan Water District of Southern California (MWD) system have, on occasion, experienced similar problems.

Recently Karimi and Singer (1991) have reported that Silver Lake Reservoir, which is part of the Los Angeles Department of Water and Power (DWP) municipal water supply system, has significantly increased algal-derived THMs. This situation arises from the chlorination of the reservoir water within the reservoir for the purposes of controlling algal growth. According to Heyer (pers. comm. 1991), the restrictions on the use of Mono Lake tributary water as a water supply source for DWP has resulted in having to use water supplied by the MWD as a source. While the Mono Lake tributary water had low algal nutrients, the MWD water is derived from the Delta and has a high algal nutrient content. According to Heyer, coincident with the switch from Mono Lake tributary water to Delta water was an increase in the algal-related water quality problems in some of the DWP reservoirs. Since the algae that are developing in some of these reservoirs (such as Silver Lake Reservoir) are not controllable by the addition of copper sulfate, this has caused DWP to initiate chlorination of the whole reservoir for the purpose of attempting to control algal growth. Karimi and Singer (1991) have found a correlation between the THMs in this reservoir water and the algae present in the water.

The Silver Lake Reservoir system is unusual because of the whole-reservoir chlorination practice. Under these conditions, the THM precursors, which are algal excretory and degradation products and the algae themselves, are converted in the lake to THMs. It therefore becomes an issue of how fast the THMs present in the lake water dissipate rather than the dissipation of algal-derived THM precursors discussed above.

The algal-related water quality problems associated with the use of Delta water as a raw water source, including increased algal-derived THMs, raises the question of whether it would be possible to control algal growth in the Delta as well as in off-Delta reservoirs filled all or in part with Delta water through the use of nutrient control at their sources for and within the Delta.

Phosphorus Sources for Delta Waters

As discussed by Lee and Jones (1988a), there are approximately fifty million people in the world whose domestic wastewaters are being treated for phosphorus removal for control of algal-related water quality problems in lakes and reservoirs. This is a well established technology typically involving the addition of alum (aluminum sulfate) as part of wastewater treatment to remove phosphorus by its incorporation into the alum floc. It is also possible to remove phosphorus through the use of biological uptake, precipitation with iron salts, or with lime. All of these methods are effective and widely practiced.

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Ordinarily, for treatment works treating over one million gallons per day, the total cost of 90-95 percent phosphorus removal from domestic wastewaters is on the order of four cents per person per day contributing wastewater to the treatment plant. It is, therefore, appropriate to investigate whether phosphorus present in Delta waters used by water utilities as a raw water source is derived from readily controllable sources such as domestic wastewaters discharged to Delta tributaries or within the Delta.

In order to estimate whether phosphorus should be removed from domestic wastewater treatment plants which contribute phosphorus to the Delta via tributaries or directly, it is necessary to estimate the total phosphorus load that stimulates algal growth in the exported water. Since in normal precipitation years the high winter-spring precipitation runoff and snow melt flows from the Sacramento and San Joaquin rivers flush the Delta and since the algal-related water quality problems associated with the use of Delta water are typically summer problems, the potential benefits for removing phosphorus from domestic wastewaters contributed to tributaries of the Delta should be evaluated for the summer.

It is estimated, based on DWR data from various sources, that the average residence time of water in the Delta during the summer months is about thirty days. This is based on an estimated volume of water in the Delta of 1 X 109 m^3 and an estimated summer inflow of 15,000 cfs. It is, therefore, evident that during the summer there is ample time for algae to develop in the Delta to the extent possible from the nutrients (nitrogen and phosphorus) present in the river inflows to the Delta. Normally, during summer months, about two weeks is necessary for algae to use all the nutrients they wish to use to develop peak biomass based on the characteristics of the waterbody.

It is possible that phosphorus added to the tributaries of the Delta during the fall, winter, and early spring could become important in causing algal-related water quality problems during the following summer in a large reservoir that is filled with Delta waters principally derived from the Delta during the fall, winter, and spring. Under these conditions, consideration should be given to year-round phosphorus removal from wastewaters and other sources should such removal be shown to have a potential benefit in reducing algal-related water quality problems for utilities using waters from that reservoir.

It is possible that phosphorus added to the tributaries of the Delta during the fall, winter, and early spring could become important in causing algal-related [reservoir] water quality problems during the...summer...

Since 1983, the California Department of Water Resources (DWR) has been conducting an extensive monitoring program of Delta waters and its major tributaries (i.e., DWR 1986 and other years). This monitoring program has included measurements of various nutrient species and planktonic algal chlorophyll. Based on review of this data, it is found that typically the concentrations of total phosphorus in the waters at the Clifton Court Forebay, where the waters are principally exported from the Delta, is on the order of 0.1 to 0.15 mg P/L. The typical tributary flow to the Delta during the summer months, according to various DWR documents, is on the order of 15,000 cfs. Using this flow and phosphorus concentrations, it is found that a total phosphorus load during the summer months of about 5×10^3 kg P/day is needed to account for the phosphorus present at the Clifton Court Forebay.

This approach assumes that all waters exported or discharged from the Delta are of the same composition as the waters at the Clifton Court Forebay. A review of the DWR data shows that the phosphorus content of the Sacramento River water near Point Sacramento and at Emmaton, both of which are just above where the main channel of the Sacramento River starts to mix with seawater, shows that the total phosphorus content of the water at this point is similar to the phosphorus content at the Clifton Court Forebay during the summer months. Therefore, the assumption that all exported or discharged water from the Delta has a composition similar to the Clifton Court Forebay waters is reasonable.

Another approach for estimating the P load to the Delta is to determine the loads at Greene's Landing on the Sacramento River and Vernalis on the San Joaquin River. Using DWR phosphorus data for the summer at these locations and typical summer flows for these rivers, it is found that the estimated phosphorus load to the Delta is about 6×10^3 kg P/day. Therefore, the Clifton Court P load data and the Sacramento and San Joaquin River P load data at Greene's Landing and Vernalis, respectively, are in agreement. It therefore appears that, at least over the summer period, the processes that take place in the Delta that remove or add phosphorus to the water tend to balance out where the phosphorus load input into the Delta is approximately equal to the phosphorus load exported and discharged from the Delta.

According to Rast and Lee (1983), the typical phosphorus per capita contribution to domestic wastewaters in the U.S. is about 1 kg P/year. According to DWR Bulletin 160, in 1987, the Sacramento River basin had about 1.87 million people and the San Joaquin River basin had about 1.18 million people. Therefore, in these two river basins there are about 3 million people that could be contributing phosphorus to domestic wastewaters that ultimately enter tributaries of the Delta. In addition, there are about 1.3 million people in the Tulare Lake basin. However, in many years, the Tulare Lake basin does not contribute water to the Delta system. For the purposes of this review, it is assumed that the 1.3 million people in the Tulare Lake basin do not contribute phosphorus to the

Delta during the summer months. It will also be assumed that between 2.5 to 3 million people in the Sacramento and San Joaquin River watersheds contribute phosphorus to the rivers or to tributaries of these rivers and ultimately into the Delta. Based on this approach about 7×10^3 kg P/day could be contributed to the Delta from domestic wastewater sources. According to Archibald (1991, this volume), the average estimated domestic wastewater flows to tributaries of the Delta is about 260 mgd (million gallons per day). Using 2.5×10^6 people as an estimate of the population contributing wastewaters to the Delta tributaries and an estimated per capita flow of about 100 gpd (gallons per day), it is found that there is agreement between the estimated domestic wastewater flow and the average measured domestic wastewater flow.

According to SWRCB (1990), the Sacramento River drains 16,960,000 acres, the Central Sierra area drains 2,432,000 acres, and the San Joaquin River drains 7,040,000 acres. Therefore, there are approximately 26 million acres that can contribute phosphorus to the Delta from land runoff above the Delta. As reported by Rast and Lee (1984) forested and agricultural lands typically contribute from 0.005 to 0.05 g $P/m^2/yr$. If it is assumed that the export of phosphorus from land in the Delta drainage basin is 0.01 g $P/m^2/yr$, it is estimated that about 3×10^2 kg P/day could be contributed by land runoff to the Delta tributaries. This approach assumes that the amount of phosphorus contributed from land runoff is equally partitioned for each day over the year. It is well known that this is not the case.

Phosphorus contributed from land runoff typically occurs during the high runoff period in the late winter and early spring. It would be expected that, except for some agricultural drainage, most of the lands in the tributaries of the Delta would contribute very little phosphorus to these tributaries in the summer months.

Another factor that would tend to make the estimated phosphorus loads from land runoff high is the fact that many of the headwaters of these tributaries contain reservoirs. Reservoirs tend to be efficient traps for phosphorus. Ordinarily, on the order of 80 percent of the phosphorus entering a reservoir is trapped within the reservoir and becomes part of the reservoir sediments. It is therefore likely that a large part of the phosphorus that would be derived from agricultural runoff above the reservoirs would not be transported to the Delta.

In addition to phosphorus contributed to the Delta tributaries from land runoff and domestic wastewater sources, consideration should be given to phosphorus sources within the Delta. There are two principal sources of phosphorus within the Delta. One of these is wastewater discharges to Delta channel waters and the other is drainage from the agricultural lands within the Delta. According to DWR (1989), there are approximately 200,000 people living in the Delta system. If all of the phosphorus in the domestic wastewaters from these people were discharged to the Delta channels, it would represent an insignificant additional source of phosphorus for the Delta. It appears, however, that a very small fraction of the wastewaters associated with this population are discharged to Delta channels that could represent a source of phosphorus for the waters exported from the Delta in the State Water Project. According to Archibald (1991, this volume), there are approximately 14,500 people living within the Delta who discharge wastewaters to the Delta. It is therefore concluded that domestic wastewater sources of phosphorus for the Delta are insignificant sources of phosphorus for the Delta.

...about 7×10^3 kg P/day could be contributed to the Delta from domestic wastewater sources.

According to DWR (1989), there are about 520,000 acres of agricultural land within the Delta. These lands are fertilized for agricultural crop production. It would be expected that part of this fertilizer would be present in the agricultural drains from the Delta islands. If it is assumed that the phosphorus export coefficients from the Delta island agricultural activities is 0.1 g $P/m^2/yr$ (a high value for most agriculture), it is found that the Delta island agricultural activities could potentially contribute on the order of 1×10^3 kg P/day to Delta channel waters.

Agee (pers. comm. 1991) provided the authors with some DWR monitoring data for the phosphorus content of agricultural drains from Empire Island within the Delta. This data covered about 2.5 years of sampling during the period 1987-1989. While the phosphorus concentration values in the drainage water were highly variable, the average of the 30 values is 0.13 mg P/L. It is therefore evident that, at least for Empire Island, the amount of phosphorus in the agricultural drainage water is about the same as the phosphorus diverted from the channels to this island. Therefore, since the load of phosphorus exported at the Clifton Court Forebay and discharged from the main stem of the Sacramento River to the San Francisco Bay system is approximately equal to the amount of phosphorus contributed to the Delta at Greene's Landing and Vernalis on the Sacramento and San Joaquin rivers, respectively, and since there are no obvious potentially large sources of phosphorus within the Delta other than agricultural drainage and since the agricultural drainage data does not show high phosphorus content compared to the Delta channel waters, it is concluded that phosphorus sources within the Delta are insignificant compared to phosphorus sources in the tributaries to the Delta.

It is, therefore, evident that the amount of phosphorus contributed from land runoff to the Delta tributaries during the summer months is insignificant compared to the amount of phosphorus derived from domestic wastewater sources which are discharged to the tributaries of the Delta. While these estimates are based on general overall characteristics of the Delta and its tributaries, it is clear that a substantial part of the summer phosphorus load to the Delta could be derived from domestic wastewaters discharged to tributaries of the Delta. These estimates indicate that domestic wastewater sources of phosphorus for the Delta could be a significant part of the total P load. Therefore, it is appropriate to pursue refining the estimates of the potential benefits of controlling phosphorus in domestic wastewaters on algal-related water quality problems for water utilities that use Delta water as a raw water source.

...significant benefits in both recreational and domestic water supply quality have been found whenever 25 percent of the total available phosphorus load is controlled.

As discussed by Jones and Lee (1986), it is important to evaluate whether at least 25 percent of the total P load for a particular waterbody is controllable in order to ascertain whether phosphorus control programs would likely produce some benefit in reduced algal biomass. It is now well established that at least this amount of phosphorus must be removed in order to cause a discernible change in algal biomass. It is highly inappropriate to assert that, in order to produce an improvement in eutrophication-related water quality, it is necessary to reduce the planktonic algal chlorophyll to less than about 5 $\mu g/L$. It is well known from actual experience that, in many waterbodies where phosphorus input control has been practiced, significant benefits in both recreational and domestic water supply quality have been found whenever 25 percent of the total available phosphorus load is controlled. The improvements in water quality occur independently of the trophic state (chlorophyll concentration) of the waterbody. The 5 $\mu g/L$ chlorophyll level value is based solely on improving the algal-related water clarity (Secchi depth) for recreational use and has little or nothing to do with domestic water supply quality or, for that matter, many of the other recreational impacts of eutrophication, such as the frequency and severity of obnoxious algal blooms that occur in a waterbody.

It is important in making the evaluation of P loads to the Delta to focus on the control of those loads that lead to algal available P in the waterbodies where there is concern about algal impacts on domestic water supply quality. As discussed by Lee et al. (1980), there are a variety of chemical and biological processes that take place in aquatic systems that convert algal available forms of phosphorus into non-available forms and vice versa. Typically, however, in rivers and in aquatic systems such as the Delta, the net conversion would likely be toward forms not available to support algal growth. It would therefore be important to conduct in-depth studies of the aqueous environmental chemistry of phosphorus in the tributaries to the Delta, within the Delta, the water export systems from the Delta, and within any off-Delta reservoirs in order to focus the phosphorus control programs on those parts of the phosphorus which are responsible for stimulating algal growth. Well established methodologies are available today to determine algal available phosphorus (Lee et al. 1980).

An additional source of phosphorus for domestic water supply reservoirs in the central and southern part of the state is the irrigation return water that enters the aqueduct system that transports water to the south and directly into some reservoirs that are part of this system. At this time the authors do not have data on the phosphorus content of the waters entering various reservoirs in the southern part of the state where algal-related water quality problems have been found. If such data does not now exist, it should be developed in order to ascertain whether there are significant sources of algal available phosphorus that could stimulate algal growth in reservoirs in the southern part of the state. If significant sources of this type exist, then phosphorus control programs should be considered for these sources. The direct addition of alum to these waters may be a highly cost effective way of removing phosphorus from sources of this type (see Lee 1973).

According to Means (1991, this volume), significant algal populations are found in the aqueduct system transporting Delta waters to the south. As part of developing algal control programs, consideration should be given to the role that algae that develop in the aqueduct play in causing algal-related water quality problems to the water utilities that use aqueduct waters as a source.

It is important to understand that the frequently used approaches for estimating whether nitrogen or phosphorus is limiting algal growth in a lake or reservoir are often inappropriate. Attempts to look at total phosphorus/nitrate ratios for estimating nutrient limitations are unreliable for estimating the impact of altering phosphorus loads to a waterbody on the planktonic algal growth that occur within the waterbody. As discussed by Lee and Jones (1981) in an AWWA Quality Control in Reservoirs Committee report, in order for nitrogen or phosphorus to limit the biomass of algae that develops in a waterbody, the concentrations of available forms must be below growth rate limiting concentrations at peak biomass when there is concern about algal-related water quality problems.

Ratios of nutrients are unreliable predictors of algal limiting nutrients and can readily lead to erroneous conclusions about the potential benefits of controlling nitrogen or phosphorus inputs to a waterbody on reducing algal-related water quality problems.

Rast et al. (1983) have shown that even though the growth rate of algae in a waterbody is not controlled by phosphorus, it is possible to use the Vollenweider-OECD modeling relationships described by Jones and Lee (1986) to predict the potential benefits of controlling phosphorus input to a certain degree on the algal-related water quality of a waterbody. As discussed by Jones and Lee (1986) and Rast et al. (1983), the Vollenweider-OECD and post-OECD database, which now exceeds over 500 waterbodies located in various parts of the world, shows that changing the phosphorus load to a waterbody produces in most waterbodies a readily predictable change in the planktonic algal chlorophyll concentration that developed in the summer within the waterbody. This relationship holds even though phosphorus is not an algal growth rate limiting element in the waterbody, i.e., phosphorus is surplus compared to algal needs. This appears to be the case throughout the Delta system and in down-Delta reservoirs.

There is a relationship between the normalized phosphorus loads to a waterbody and the planktonic algal chlorophyll that develops within the waterbody. The normalizing factors are the waterbody's mean depth and hydraulic residence time. The normalizing term has been found to be approximately equal to the annual phosphorus concentration in the waterbody. Therefore, the relationship, in its most basic terms, is simply a statement of algal stoichiometry in which there is a correlation between the phosphorus concentration in a waterbody and the algal growth that occurs in the waterbody. While this relationship is not applicable to all waterbodies, it is applicable to well over 80 percent of the world's freshwater waterbodies. Jones and Lee (1986) provide guidance on how to determine its applicability to a particular waterbody.

The DWR monitoring data for the Delta waters shows that nitrogen is not limiting algal growth in these waters.

In order for the growth of algae in a waterbody to be proportional to the available phosphorus concentrations in the water, even though phosphorus is not limiting their rate of growth, it is necessary that all other nutrients needed by the algae be present in surplus amounts, compared to algal needs. The chemical typically of greatest concern is nitrogen in the form of nitrate and/or ammonia. The DWR monitoring data for the Delta waters shows that nitrogen is not limiting algal growth in these waters. Further, since algal growth in the Delta is about equal to what is predicted based on phosphorus chlorophyll relationships for waterbodies located throughout the world, it appears that all other elements needed for algal growth are present in sufficient concentrations to allow growth to the extent possible based on the characteristics of the Delta and the phosphorus loads.

From the information available at this time, it appears that phosphorus should be added to the list of contaminants of Delta system waters that should be investigated for the possible development of control programs. There is a potential for such programs to significantly improve the algal-related tastes and odors and other domestic water supply quality problems, including THM precursor formation, through phosphorus control in the Delta system and its tributaries. Such control programs could affect domestic water supply quality for many millions of people in California.

Impact of Phosphorus Control on Delta Fisheries

One of the potential consequences of phosphorus control for tributaries of the Delta and in the Delta is decreased fish production within the Delta. Jones and Lee (1986) have reported a strong, highly significant relationship between the phosphorus loads to waterbodies located in various parts of the world and the fish production within these waterbodies. Basically, the relationship is one of increased primary production (algae) in lakes and reservoirs resulting in increased secondary (zooplankton) and tertiary (fish) production. Since the primary productivity and algal biomass in many lakes and reservoirs, as well as other waterbodies, is correlated with the phosphorus concentration within the waterbody, and since phosphorus concentrations within the waterbody can be correlated with phosphorus loads when normalized by the waterbodies' hydrological and morphological characteristics, it is not surprising that a relationship is found between normalized phosphorus loads in lakes and reservoirs located in various parts of the world and fish production. Therefore, decreasing the phosphorus loads to the Delta will likely decrease the fish production within the Delta.

Using the relationship developed by Jones and Lee (1986), between normalized phosphorus loads and fish production, it is found that in the range of planktonic algal chlorophylls of concern within the Delta system that a 50 percent reduction in the phosphorus load to the Delta would be expected to decrease fish production by 40 to 60 percent dependent upon the planktonic algal chlorophyll concentration. While there may be some who assert that decreasing phosphorus loads to the Delta system should not be practiced because of the adverse effects on the fisheries of the Delta, it is clear that the problems of the fisheries of the Delta are not fish food supply related and therefore controlling phosphorus inputs will have little or no impact on fish production for the fish species of primary concern in the Delta, such as striped bass. Phosphorus control, however, will almost certainly have an impact on the rough fish population, such as carp.

MANAGEMENT OF EUTROPHICATION

Lee and Jones, through their activities in the AWWA Quality Control in Reservoirs Committee, developed a report that was reviewed and approved by the committee and which serves as a guide to water utilities on the approaches that should be considered in evaluating whether phosphorus control from watershed sources could be a potential benefit in improving a water utility's domestic water supply raw water quality. An example of the application of the evaluation of the potential benefits in controlling phosphorus loads to a domestic water supply reservoir is provided for Lake Ray Hubbard, a city of Dallas, Texas water supply reservoir (Archibald and Lee 1981).

...it is clear that the problems of the fisheries of the Delta are not fish food-supply related and therefore controlling phosphorus inputs will likely have little or no impact on fish production for the fish species of primary concern...

There are a variety of techniques that have been used with success in some locations for management of eutrophication of waterbodies. Generally, the utility of these approaches has been judged based on improvement of recreational uses of the water. Thus far, inadequate attention has been given to the improvement of domestic water supply raw water quality. A review of the various techniques that have been used for managing eutrophication has been published by Lee (1973) and by Cooke et al. (1986).

While there are several techniques, such as aeration, dredging, manipulation of fish and other aquatic organism populations, aquatic weed harvesting, etc., that have been used with some success for managing eutrophication-related recreational impacts in lakes and reservoirs, it is questionable whether many of these techniques have applicability to significantly improving domestic water supply eutrophication-related water quality. For example, one of the techniques that is often said to be beneficial for managing eutrophication related water quality in lakes and reservoirs is aeration-destratification of the waterbody. This technique, however, does not necessarily improve eutrophication-related water quality for recreational and domestic water supply uses.

The value of aeration of reservoirs in improving domestic water supply quality was reviewed by the AWWA Quality Control in Reservoirs Committee. This committee reported that after extensive review of the data available, there were serious questions as to whether aeration of a water supply reservoir would improve water quality. It was found that in some water supply reservoirs, aeration caused greater algal-related water quality problems than occurred in the unaerated reservoirs. This situation is to be expected in stratified reservoirs where the thermodine serves as an effective barrier to nutrient regeneration and transport from the deeper waters of the lake to the surface waters where the algae develop. The aeration-destratification of a water supply reservoir, however, should be evaluated cautiously. It appears that in some instances, but not all, there are benefits in domestic water supply quality associated with aeration-destratification of the waterbody. As discussed by Lee (1973), hypolimnetic aeration of reservoirs in which destratification does not occur has been found to be an effective method of improving the domestic water supply quality of hypolimnetic waters.

With increased attention being given to control of THMs in treated waters, emphasis should be placed on understanding the sources of organic THM precursors.

It is important for water utilities that are facing eutrophication-related water quality problems to focus their efforts to the greatest extent possible on controlling algal nutrients. Efforts to control eutrophication by other methods must be carefully evaluated.

CONCLUSIONS

It is concluded that, because of the importance of the Delta as a water supply source for two-thirds of the population of California, a much greater effort should be devoted to source water quality control for contaminants that directly (or indirectly, as in the case of phosphorus) cause significant water quality problems for water utilities that use Delta waters as a source of supply. Understanding the specific sources of various contaminants and investigating the potential for control of these contaminants at the source could be significantly beneficial in improving domestic water supply quality for many of the people in California.

With increased attention being given to control of THMs in treated waters, emphasis should be placed on understanding the sources of organic THM precursors. A significant effort should be made to develop THM precursor land use-export coefficients. Water utilities using Delta water as a source, as well as regulatory agencies, should determine the dominant sources of THM precursors in the Delta and its watershed and evaluate on a site-specific basis the potential for control of the most significant sources. THM precursor control programs should be initiated in those situations where the collective development of such a control program would result in a significant lowering of the THMs produced upon disinfection of the water supply.

Municipal water utilities that use the Sacramento-San Joaquin River Delta as a water supply source, and the regulatory agencies as well, should investigate the potential benefits of the control of phosphorus in domestic wastewater sources discharged to tributaries of the Delta. It has been found that during the summer months, domestic wastewater sources are the primary source of phosphorus for the Delta system. Phosphorus control from these sources with readily available widely practiced technology could result in a significant reduction of algal growth within the Delta and in down-Delta reservoirs as well as in the aqueduct system. Such reduced growth could significantly reduce the algal-related taste and odor problems as well as algal-derived THM precursors.

Acknowledgements

The authors wish to acknowledge the assistance provided by several individuals in developing this paper. Numerous members of the California

Department of Water Resources were helpful in providing information. Of particular significance were Dr. S. Hayes, B. Agee, R. Woodard, and R. Zettlemeyer. The assistance of Dr. D. Carlson of the Water Resources Control Board staff in obtaining background information for this paper is also acknowledged. W. Heyer and Dr. A. Kamini of the Los Angeles Division of Water and Power, E. Means and R. Clemmor of the Metropolitan Water District of Southern California, and several individuals with the Sacramento Office of the U.S. Geological Survey provided important background information for this paper.

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